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Correlations between cone penetration test and seismic dilatometer Marchetti test with common laboratory investigations

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Abstract

During the last decade, due to the increasing need for commercial spaces with access to the subway, tall buildings were constructed in the north of Bucharest. These buildings transmit high loads on the foundation ground and require foundation systems that ca ensure low-grade settlements, while the influence on the surrounding area is minimized. To achieve this with a sustainable economic and low environmental impact, common geotechnical investigations and advanced ones need to be corroborated in order to provide reliable input data for an accurate FEM analysis.
This paper presents some correlations between Cone Penetration Tests (CPT) and Flat Dilatometer Marchetti Tests equipped with seismic module (SDMT) with common laboratory geotechnical investigations. It is aimed to achieve a better understanding of the obtained geotechnical parameters and the correlations between them, justifying the investigation effort and enabling reliable input data for advanced FEM analysis.

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Keywords: Geotechnical investigations; tall building; subway; stiffness; seismic

1. Introduction

The present paper presents the interpretation of some geotechnical investigations, focussing on the comparison between SDMT, CPT and laboratory test results that were used to define the geotechnical model. In the north of Bucharest, a new commercial and business area is developing, taller buildings being constructed on the entire area.

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From the geomorphological point of view, the area is classified as high plain with good foundation ground for typical buildings (without many underground levels and of medium height).

The structure this paper refers to has a total area of 9500 m^2 – and is divided in two buildings, Building A – Tower with a height of *3UG+G+M+22S+23SR+ET* and Building B – Parking with a height of *2UG+G+1S*. In case of Building A, there must be noted that the loads transmitted to the foundation ground are high and asymmetric. Also, the metro galleries are placed near the foundation of the building and the uplift conditions have to be verified.

These premises led to complex ground investigations, including Cone Penetration Tests (CPT), Seismic Flat Dilatometer Marchetti Tests (SDMT) and laboratory investigations to define the geotechnical model.

2. Geotechnical Investigations

The type of the investigations, number and location were chosen in order to evaluate the soil properties, given the loads transmitted by the structure to the foundation ground, by the geotechnical designer considering the parameters necessary for the analysis.

In order to design the deep foundations and the excavation for the new earthquake-resistant structures, the soil layers were investigated in terms of strength and deformability parameters. Thus, over the entire area of the site the following investigations were performed.

Three deep boreholes with depths of 60 m, 42.5 m and 20 m from which soil samplings were collected. On the soil samples, laboratory investigations were performed in order to describe the stratigraphy and to evaluate the strength and stiffness parameters. The laboratory investigations consisted in tests to determine the soil indices (grain size distribution, humidity and Atterberg limits) and the mechanical parameters by oedometric tests and direct shear tests.

Six Cone Penetration Test (CPTs) were performed with depth varying from 24.9 to 43.6 m. One CPT location was doubled by a Seismic Marchetti Dilatometer Test with a depth of 41.2 m.

The in situ testing offered a detailed characterization from lithological, strength and stiffness point of view. The seismic module of the SDMT, provided shear wave velocity vs data which was used to determine the G0 module for each soil layer in order to analyze the seismic ground response.

The data presented in this paper is focused on one investigation point where the all types of investigations were performed.

2.1. Cone Penetration Test (CPT)

The CPT advantages, over the traditional geotechnical investigations such as drilling, sampling and laboratory investigations, are the following. It is fast (20 m of penetration in 30 minutes), repeatable and it provides near continuous data.

Major research works have been carried on by Robertson [1]. Notable interpretations of the CPT have been published by Lunne et. Al [2] and Mayne [3].

One major application of the CPT is soil profiling and classification. Typically, the cone resistance, qc, is high in sands and low in clays and the friction ratio, Rf (equation 1), is low in sands and high in clays.

$$R_f = f_s/q_c \tag{1}$$

where,

R_f – the friction ratio

f_s – sleeve friction in MPa

q_c – cone resistance in MPa

2.2. Seismic Dilatometer Marchetti Test (SDMT)

The Seismic Dilatometer Marchetti Test (SDMT) is an efficient method for estimating, quickly and accurately, the compressibility characteristics of the soils. These are used as input parameters in advanced design models to assess the building settlement and soil deformations.

The flat dilatometer consists of a steel blade (95x200x15 mm) having on one face an expandable steel membrane. A gas tank supplies the gas pressure required to expand the membrane. As the membrane expands, the soil is slightly compressed. Three readings are taken, at specific moments of the test. Soon after, the blade is advanced to the next investigation depth.

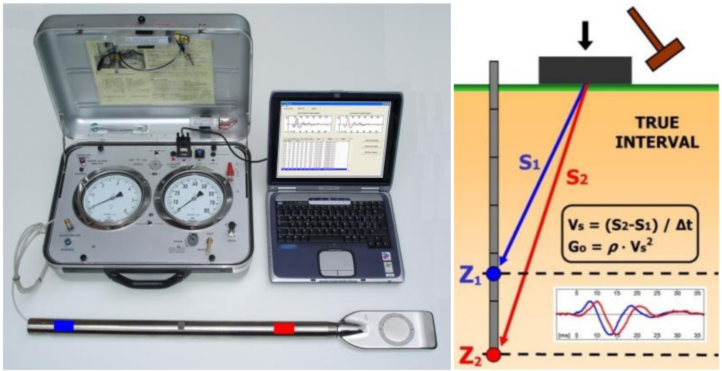

Fig. 1. The seismic dilatometer equipment and schematic layout of the seismic dilatometer test

The main use of the SDMT (Fig. 1) investigations is to obtain the geotechnical parameters of the soil and the soil profile by corroborating the results with the laboratory investigations. When equipped with the seismic module, dynamic properties of the soils can be determined directly and precisely.

2.3. Undrained shear strength

The shear strength is used in soil mechanics to characterize the shear stress that a certain soil can sustain. The shear resistance of a soil is the result of friction and arrangement of particles and possibly cementation or bonding at particle contacts.

The undrained shear strength, su, describes the shear stress that a soil can sustain in short term conditions. It is an important parameter that is found in many geotechnical constitutive models. It can be obtained by a simple shear strength test, but its value is dependent on sampling, transporting and laboratory operator experience.

The s_u from DMT, was obtained by applying Marchetti (1980) [4] correlation.

$$s_u = 0.22 * (0.5 * K_D)^{1.25} * \sigma'_{v0} \quad (3)$$

su – undrained shear strength in kPa

KD – Horizontal Stress Index

The undrained shear strength was estimated using the cone resistance qc, according to T. Lunne, P.K. Robertson, J.J. Powell [5]:

$$s_u = \frac{q_c - \sigma_{v0}}{N_k} \quad (4)$$

where,

su – undrained shear strength in kPa

qc – cone resistance in kPa

σ_{v0} – total in situ vertical stress in kPa

Nk – empirical cone factor

A large number of studies were undertaken by numerous authors in order to estimate the cone factor for different soil types. According to the paper of Zsolt Remai [6], the cone factor has usually values of Nk=10...28. In this particular case, the Nk values were determined by corroborating it with the undrained shear strength obtained in the laboratory, as shown in table 3.

The correlation proposed by Trofimencov [7] was also used in determining the undrained shear strength. Although Trofimencov formula gives the cohesion, the undrained shear strength can be obtained by applying the relation proposed by Lunne & Lacasse [8].

$$c = 0.0116 * q_c + 0.0125 \quad (5)$$

$$c = 0.5 * s_u \quad (6)$$

where,
c – cohesion in kPa
qc – cone resistance in kPa
su – undrained shear strength in kPa

2.4. Elasticity Modulus

The oedometer test is used in geotechnical investigations to measure the soil compressibility and consolidation properties. It is performed by applying different loads to a soil sample while measuring the deformation and time. It is a simple laboratory investigation. It is delicate and the results in terms of deformation moduli are user/sampling method dependent.

The correlation between CPT raw data and E modulus were determined using formulas proposed by Vesic [9] (eq. 7, 8), Kulhawy & Mayne [10] (eq. 9)

$$E = 3.8 * q_c + 4 \quad (7)$$

$$E = 2 * (1 + I_D^2) \quad (8)$$

$$E = 8.25 * (q_c - \sigma_{v0}) \quad (9)$$

where,
E – Young Modulus in kPa
I_D – soil type index
q_c – cone resistance in kPa
σ_{v0} – total in situ vertical stress in kPa
The modulus obtained by oedometric tests were corrected with the M_0 value, provided by STAS 3300/2-85

2.5. Shear waves velocity, vs

In order to determine the shear waves velocities the Seismic module of the SDMT was used. The shear waves are generated at the surface by stroking a steel plated wooden box by hammer. The shear wave velocity is obtained as the ratio between the difference in distance from the source and the two receivers (S2 – S1) and the time delay needed by the impulse to reach the first and second receiver (Δt), as shown in Fig. 1.

The investigations of the shear wave velocity is useful for the advance design of the deep excavations and foundations due to the possibility of estimating the G_0 modulus. The G_0 modulus, also known as small strain stiffness modulus, is used as one of the input parameters in HS Small (Hardening Soil with Small Strain) model used in Plaxis finite element analysis.

The v_s profile and thus the G_0 values can be determined by correlating the DMT and CPT data. The correlations used in the present paper to predict v_s from CPT investigations are those of Robertson et al. (1992) [11]:

$$v_s = 60.3 * q_c^{0.23} \quad (10)$$

where,
v_s – shear wave velocity in m/s

q_c – cone resistance in MPa
Marchetti et al. 2008 [12] proposed formulation to estimate the G_0 module from the DMT raw data.

$$I_D < 0.6 => \frac{G_0}{M_{DMT}} = 26.177 * K_D^{-1.066} \tag{11}$$

$$0.6 < I_D < 1.8 => \frac{G_0}{M_{DMT}} = 15.686 * K_D^{-0.921} \tag{12}$$

$$I_D > 1.8 => G_0/M_{DMT} = 4.5613 * K_D^{-0.7967} \tag{13}$$

where,
I_D – soil type index
G_0 – maximum shear modulus
M_{DMT} - constrained modulus
K_D - Horizontal stress index

3. Results of the geotechnical investigations

The obtained geotechnical parameters were analyzed and defined by interpreting the results from in situ and laboratory investigations.

The soil is a material characterized by high heterogeneity and variability of its parameters. In order to provide a safe, economic and environmental friendly design, the main parameters, obtained from geotechnical investigations, will be compared, in order to evaluate the reliability of each investigation. The overall data analysis was used as input data for a geotechnical model.

A geotechnical model is described by a set of parameters. In order to describe mathematically the mechanical response and behaviour of a soil, a geotechnical model is corroborated with a constitutive model.

3.1. Soil Profiling and Classification

When creating a geotechnical model, it is important to accurately define the stratigraphic profile in order to assess and classify the soil layers that have close mechanical response. The soil profiles were obtained as follows: During drilling, the borehole log was recorded so that a primary soil profile was determined. It was detailed and completed after the laboratory investigations.

To detail the soil profile of the entire area of the new building, using well established correlations, the soil stratigraphy was also obtained from CPT and SDMT data. The soil profiles obtained from the borehole log, CPT and DMT investigations are presented in Fig. 2 and Table 1.

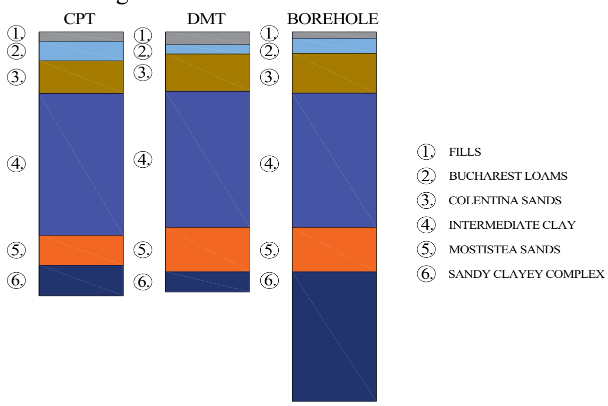

Fig. 2. Soil profile obtained from CPT, DMT and BOREHOLE investigations

Table 1. Soil Profiles

Soil Description	CPT Layer Depth [m]	DMT	BOREHOLE
Layer 1 - Fills	0.00 - 1.52	0.00 - 2.00	0.00 - 1.00
Layer 2 - Bucharest Loams	1.54 - 4.58	2.00 - 3.50	1.00 - 3.40
Layer 3 - Colentina Sands	4.58 - 9.74	3.50 - 9.40	3.40 - 9.70
Layer 4 - Intermediate Clays	9.74 - 32.20	9.40 - 32.00	9.70 - 31.00
Layer 5 - Mostiştea Sands	32.20 - 36.94	32.00 - 38.00	31.00 - 38.00
Layer 6 - Sandy Clayey Complex	36.94 - 41.78	38.00 - 41.20	38.00 - 58.50

3.2. Undrained shear strength

The undrained shear strength, su, was obtained by multiple ways as shown in Figure 3, for example the direct shear laboratory tests (CU type – consolidated - undrained) and via correlations from CPT and DMT. A comparison of the results is shown in Table 2. This evaluation is useful because it shows the correlation between different investigations in order to better understand the soil behaviour.

As shown in Table 2, the correlation between the different investigation methods is reasonably good for the first layers.

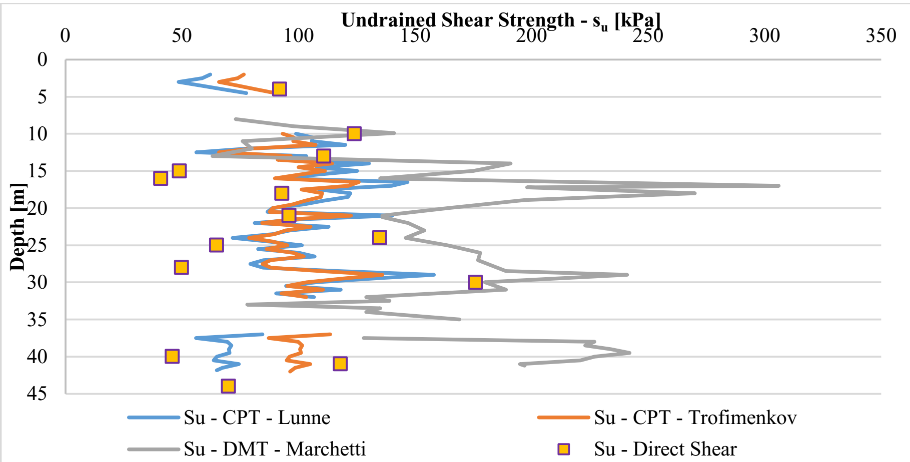

Fig. 3. Undrained Shear Strength obtained from CPT, DMT and Direct Shear Test

Table 2. Undrained Shear Strength

Soil Description	CPT su [kPa]		DMT	Direct Shear (CU)
Layer 1 - Fills	-	-	-	-
Layer 2 - Bucharest Loams	86*	90**	74	63
Layer 3 - Colentina Sands	-	-	-	-
Layer 4 - Intermediate Clays	92*	94**	142	73
Layer 5 - Mostiştea Sands	-		-	-
Layer 6 - Sandy Clayey Complex	104*	106**	208	52

* Trofimencov 1995

** T. Lunne, P.K. Robertson, J.J. Powell 1997

Table 3. Cone factors values for different soil layers in Bucharest

Soil Description	Nk
Layer 2 - Bucharest Loams	35
Layer 4 - Intermediate Clays	28
Layer 6 - Sandy Clayey Complex	40

3.3. Elasticity Modulus

On each soil layer it is preferred to rely on as many soil sample as possible. Ideally, each borehole should be doubled by in situ tests that offer results obtained on the undisturbed soil.

The SDMT was designed to investigate soil stiffness and deformation characteristics with minimum disturbance. Its results were widely investigated and analyzed and their reliability was confirmed by many research works.

In Table 4 and in Figure 4 the Elasticity Modulus obtained by oedometric laboratory investigations, CPT and DMT is presented. It must be noted that M_{DMT} is not equal to E.

Table 4. Elasticity modulus obtained by CPT, DMT and Oedometer investigations

Soil Description	CPT E [MPa]		DMT [M]	Oedometer
Layer 1 - Fills	-	-	-	-
Layer 2 - Bucharest Loams	12*	21**	23	13
Layer 3 - Colentina Sands	41*	58**	19	-
Layer 4 - Intermediate Clays	14*	22**	26	16
Layer 5 - Mostiştea Sands	33*	82**	18	-
Layer 6 - Sandy Clayey Complex	16*	24**	30	16

*Marcu 1995 and Vesic 1968

** Kulhawy & Mayne 1990

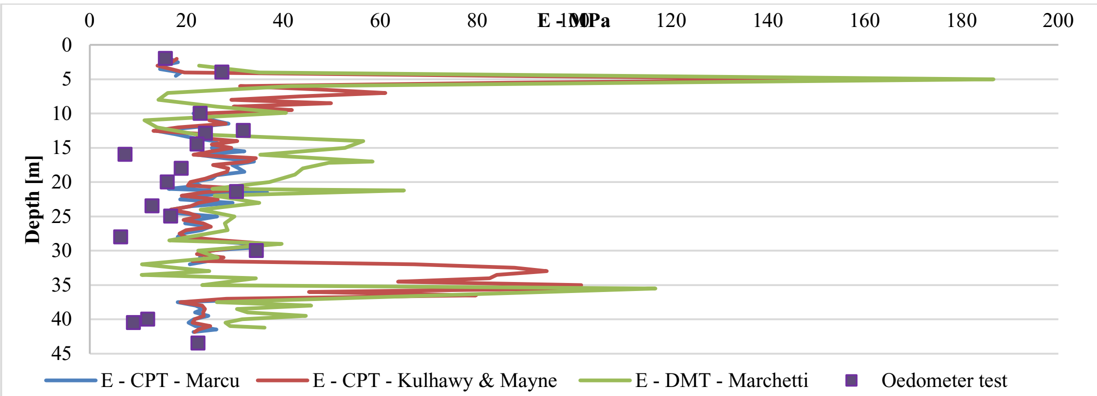

Fig. 4. Elasticity modulus obtained from CPT, DMT and Direct Shear Test

3.4. Shear wave velocity, v_s

The comparisons between the measured values of v_s and the estimated values from CPT and DMT are shown in Table 5. It can be seen from Figure 5 that even though the v_s profiles obtained using Robertson et al. (1992) [11] and Marchetti et al. 2008 [12] are comparable, they can underestimate the measured v_s values by more than a half.

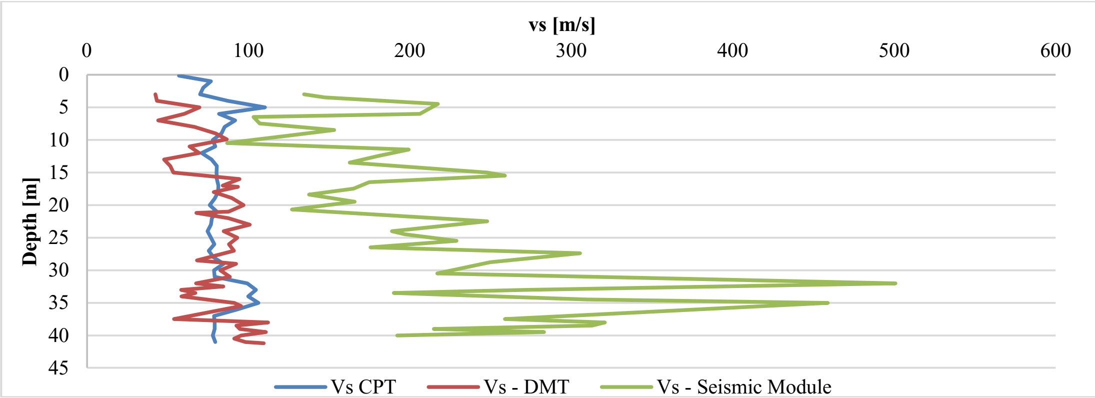

Fig. 5. Shear wave velocity obtained from CPT, DMT and Seismic Module

Table 5. Shear wave velocity obtained by CPT, DMT and Seismic Module

Soil Description	CPT	DMT	Seismic module
	vs [m/s]		
Layer 1 - Fills	-	-	-
Layer 2 - Bucharest Loams	73	79	135
Layer 3 - Colentina Sands	92	80	125
Layer 4 - Intermediate Clays	78	98	170
Layer 5 - Mostiștea Sands	102	115	260
Layer 6 - Sandy Clayey Complex	79	100	205

4. Conclusions

In this paper various type of investigations are presented, focusing on evaluating how each type of survey is able to determine a certain soil characteristic or parameter (Soil profile, su, E, vs). The soil profiles obtained by all types of investigations offer close results. A particular attention was given on the results obtained by SDMT and CPT. Specific Nk – cone factors were determined for the cohesive soils in Bucharest and there values are presented in table 3. In general, the DMT results show a stiffer response of the soil if these are compared with the values obtained by laboratory investigations. Also, the correlation of CPT data used to determine the elasticity modulus proposed Vesic offer the best results when comparing with the parameters obtained in laboratory. The CPT - vs and DMT - vs correlations underestimate by half the measured velocity of the shear waves.

Further research is planned to be done, in order to closer calibrate the parameters described in this paper with the soils specific to Bucharest, Romania.

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